BOREAL ENVIRONMENT RESEARCH 13: 231–241
ISSN 1239-6095 (print) ISSN 1797-2469 (online)

Helsinki 25 June 2008

Gaseous nitrogen and carbon fluxes in riparian alder stands

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Received 1 Nov. 2006, accepted 19 Mar. 2007 (Editor in charge of this article: Raija Laiho; guest editor: Adel Shirmohammadi)

Mander, Ü., Lõhmus, K., Teiter, S., Uri, V. & Augustin, J. 2008: Gaseous nitrogen and carbon fluxes in riparian alder stands. *Boreal Env. Res.* 13: 231–241.

Riparian buffer zones are considered to be important elements of agricultural watersheds, in that they control nutrient and carbon fluxes. Although the water purification effect of riparian ecosystems has been well studied, there is little knowledge of their internal cycling, especially in the area of gaseous emissions. We measured fluxes of nitrous oxide (N_2O), dinitrogen (N_2), methane (CH_4), and carbon dioxide (CO_2) in riparian grey alder stands in southern Estonia and black alder stands in Brandenburg, Germany. Dinitrogen emission was the most important component in N retention in the studied riparian grey alder forests. In 2001–2003, the median values of N_2 emission in the grey alder sites significantly exceeded the N_2 emission rates in the black alder sites, varying from 700 to 1200 and from 360 to 400 kg N_2-N ha^{-1} $year^{-1}$, respectively. In contrast, the median values of N_2O flux were higher in the black alder sites than in the grey alder sites, i.e., 0.9–2.6 and 0.2–0.7 kg N_2O-N ha^{-1} $year^{-1}$, respectively. The black alder sites acted as a sink for CH_4, whereas the grey alder sites emitted a small amount of CH_4. The CO_2-C flux was higher in the black alder stands. The estimated N_2-N emission in the grey alder stands for 1994–1995 was 51.2, whereas N_2O-N emission was 0.5 kg N ha^{-1} $year^{-1}$. The significant increase in N_2 emission from 1994–1995 to 2001–2003 can be related to changes in microbial activity during the succession of the pioneer grey alder stand into a more stable mixed forest community. Due to CO_2 fluxes and N_2O fluxes from sites with altered water regime, the estimated GWP of the studied riparian alder stands was relatively high. Further investigations should concentrate on the factors that regulate rates of N_2O and N_2 emission from riparian buffer zones.

Introduction

In their role as the interface between terrestrial and aquatic components of the landscape, riparian buffer zones are important ecotechnological measures to control water quality in agricultural catchments (Kuusemets and Mander 1999). Although the water purification effect of riparian ecosystems has been thoroughly studied (Haycock and Pinay 1993, Vought *et al*. 1994, Mander *et al*. 1995, 1997a), little is known about their internal cycling (Lowrance *et al*. 1983, Peterjohn and Correll 1984), especially concerning gaseous emissions (Groffman *et al*. 1991,

Teiter and Mander 2005). Moreover, some studies have shown that water purification efficiency can be less favorable in riparian zones, which function as hotspots of greenhouse gas emissions with high global warming potential (GWP; Groffman *et al*. 2000).

Alders are known as a host species of symbiotic dinitrogen (N_2) fixing bacteria (actinobacteria) from the *Frankia* group (Rytter *et al*. 1989). Due to high rates of N_2 fixation, some authors have seen alder forests as sources of water body pollution with excess nitrogen (N) (Binkley *et al*. 1992). Several other studies consider riparian alder stands to be effective N removal ecosystems (Mander *et al*. 1995, 1997a, 1997b). This contradiction is mainly due to the positioning of alder stands in the landscape: in riparian zones the excess N is mainly denitrified, whereas in more aerated conditions of higher altitude locations (*see* Binkley *et al*. 1992) leaching takes place. Denitrification, which is generally referred to as the microbial reduction of nitrate-N (NO_3-N) to nitrite-N (NO_2-N) and further to the gaseous forms nitric oxide (NO), (nitrous oxide) N_2O and N_2 (Knowles 1982), has been found in numerous studies to be a significant process in N removal in riparian buffer zones (Groffman *et al*. 1991, Ambus and Christensen, 1993, Hanson *et al*. 1994, Weller *et al*. 1994, Gold *et al*. 1998, Hefting and Klein 1998, Groffman *et al*. 2000). In the majority of these studies, N_2O fluxes have been measured, while only a few studies pay attention to N_2 emission (Watts and Seitzinger 2000, Butterbach-Bahl *et al*. 2002).

Nitrous oxide, as one of the greenhouse gases, is increasing in the atmosphere at a rate of about 0.3% year^{-1} (Mosier 1998). It has an atmospheric lifetime of about 120 years, a GWP of 296 relative to carbon dioxide (CO_2), over a 100-year time horizon, and is responsible for about 5% of the anticipated warming (IPCC 2001). Riparian zones have the potential to be hotspots of N_2O production in the landscape (Groffman *et al*. 2000). Likewise, riparian wetlands and wet riparian forests can be sources of methane (CH_4) (Jones and Mulholland 1998, Rush and Rennenberg 1998), which is another greenhouse gas that is increasing in the atmosphere at a rate of about 0.8% year^{-1} (Mosier 1998). Methane in the atmosphere has a lifetime of 8.4 years. On a 100-year time horizon, CH_4 has a global warming potential of 23 relative to CO_2, and is responsible for about 20% of anticipated warming (IPCC 2001).

Both denitrification and CH_4 formation depend on the oxygen status of the soil or sediment. As a result, the spatial and temporal variability of fluxes of both N_2O (Robertson and Tiedje 1984, Ambus and Christensen 1993, Augustin *et al*. 1998, Gold *et al*. 1998, Jacinthe *et al*. 1998) and CH_4 (Saarnio *et al*. 1997, Willison *et al*. 1998) are high. Denitrification rates in soils are mainly influenced by carbon availability, NO_3^- availability, temperature and pH (Nõmmik 1956, Knowles 1982). Methane is produced in anoxic soils and sediments, while well-drained soils act as a sink for atmospheric CH_4 due to CH_4 oxidation, through either ammonia oxidizers or methanotrophs (Hanson *et al*. 1993).

Several studies consider CO_2 emissions and sequestration in riparian wetlands (Mitsch and Gosselink 1993) and buffer zones (Brumme *et al*. 1999, Gulledge and Schimel 2000, Tufekcioglu *et al*. 2001, Larmola *et al*. 2003, Scott *et al*. 2004, Teiter and Mander 2005, von Arnold *et al*. 2005) Depending on meteorological and hydrological conditions, riparian ecosystems, especially wetlands, can be either sources or sinks of carbon (C) (Gulledge and Schimel 2000).

The main objectives of this research were to quantify and compare N_2O, N_2, CH_4 and CO_2 emission rates in two different riparian alder forests: grey alder, *Alnus incana*, and black alder, *A. glutinosa*, and to estimate the global warming potential (GWP) of the analyzed greenhouse gases. Based on our measurements and data from an earlier study, we further estimate the role of N_2O and N_2 emission in the nitrogen budget of the grey alder stand.

Material and methods

Study sites

The Porijõgi study area represented a grey alder stand. It is situated in the moraine plain of southeastern Estonia (Tartu County, Sirvaku; 58°13´N, 26°47´E), in the riparian zone of a small river, the Porijõgi, which flows in a primeval valley where

agricultural activities ceased in 1992. The landscape study transect in this valley crosses several plant communities: an abandoned field (last cultivated in 1992) on Planosols and Podzoluvisols; an abandoned cultivated grassland (last mown in 1993) on Colluvial Podzoluvisol (dominated by *Dactylis glomerata* and *Alopecurus pratensis*); an 11 m wide wet grassland on Gleysol (two parallel communities, one dominated by *Filipendula ulmaria,* another by *Aegopodium podagraria*) and a 20-m wide grey alder stand on Mollic Gleysol. In the grey alder stand, 3 sites: Edge, Wet and Dry were chosen for gas and soil analyses. The main soil characteristics of the Porijõgi study area are presented in Table 1. For a more detailed description *see* Kuusemets *et al*. (2001).

The Gumnitz study area is located in Müncheberg (52°50´N, 14°14´E) in Brandenburg State in northeastern Germany. Vegetation cover at this site represented a black alder forest on Gleysols and Histosols, more specifically a *Carici acutiformis–Alnetum* community, in which *Carex acutiformis* and *Carex canescens* dominated. The Gumnitz A site represented a riparian alder stand with lowered water table due to drainage, whereas the Gumnitz B has an unchanged water regime. The main soil characteristics of the two riparian study sites Gumnitz A and Gumnitz B are presented in Table 1.

Gas sampling and analyses

For the measurement of N_2O, N_2, CH_4 and CO_2 emissions, the closed chamber method (Hutchinson and Livingston 1993) and the He-O method (Butterbach-Bahl *et al*. 1997, Scholefield *et al*. 1997, Mander *et al*. 2003) were used. The latter allows measurement of N_2 fluxes. Five gas samplers were installed: one at each of the 3 different sites (Edge, Wet and Dry) in the Porijõgi riparian buffer zone, and on the stream bank (A) and the alder stand edge (B) in Gumnitz. The samplers were closed chambers with a cover made of PVC, height 50 cm, ∅ 50 cm, volume 65 l, sealed with a water-filled ring on the soil surface, painted white to avoid heating during application.

Gas sampling was carried out according to the following schedule: (1) in Porijõgi, once a month in May, June and September 2000, October and November 2001, March, May to December 2002, and January to March, July and October 2003; (2) in Gumnitz, 3–4 times a month from January to September 2000 and once a month in January and May 2001 and in May 2002. At the end of the 1-hr measuring period, gas samples were taken from the enclosures of samplers with previously evacuated gas bottles (100 ml; *see* Augustin *et al*. 1998). The soil temperature and redox potential, and water depth in the sampling wells was measured simultaneously, and the NH_4-N and NO_3-N concentration in soil samples was analysed using the Kjeldahl method (APHA 1989).

Intact soil cores (diameter 6.8 cm, height 6 cm) for use with the He-O method were taken from the topsoil (0–10 cm) at the gas sampler sites each time after gas sampling was completed. Soil samples were weighed, kept at low temperature (4 °C) and transported to the laboratory of the Institute of Primary Production and Microbial Ecology of the Centre for Agricultural Landscape and Land Use Research (ZALF) in Germany. At the lab, the soil cores were introduced into special gas-tight incubation vessels. In these vessels, N_2 was removed using 3 sub-

Table 1. Main soil characteristics of the study sites.

Study site	Average water table (m)	pH	Dry matter (%)	N (%)	NH_4^+-N (mg 100 g^{-1})	NO_3^-N (mg 100 g^{-1})	C (%)
Gumnitz A	0.60	5.2	39.8	1.6	0.43	20.90	20.1
Gumnitz B	0.02–0.04	5.7	25.7	1.9	0.46	14.30	39.5
Porijõgi Wet	0–0.05	6.5	55.0	0.4	1.88	0.09	4.0
Porijõgi Dry	0.45–0.95	6.3	44.4	0.8	0.33	0.14	4.5
Porijõgi Edge	0.45–0.95	6.3	65.5	0.3	0.61	0.11	5.3

sequent slight evacuation/flushing cycles with an artificial gas mixture (21.3% O_2, 78.6% He, 337 ppm CO_2, 374 ppb N_2O, 1882 ppb CH_4 and approximately 5 ppm N_2). This was followed by the establishment of a new flow equilibrium by continuously flushing the vessel headspace with the gas mixture at 10 ml per minute for 12 hours. For the start value, N_2 and the greenhouse gas concentration in the gas mixture was measured. The gas concentrations in the incubation headspace were measured (final value) after closing the incubation headspace for one hour to accumulate the emission of N_2 and the greenhouse gases. The final accumulation value minus the start continuous flow value served as the basis for the calculation of the emission rates. During the flushing the redox potential of the soil cores was regularly measured and regulated so that it was comparable with the field conditions. The gas concentration in the collected air was determined by using gas chromatograpy (electron capture detector and flame ionization detector; Loftfield *et al*. 1997) in the lab of the Institute of Primary Production and Microbial Ecology, Centre for Agricultural Landscape and Land Use Research (ZALF), Germany. The procedures used for the determination of the emission rates of gases are described by Mander *et al*. (2003).

Water sampling and analyses

In Porijõgi, shallow groundwater samples from the upper aquifer were collected once to twice a month from 6 piezometers, 3 of them installed on the upper border and 3 within the grey alder stand. The depth of ground water varied from 10–80 cm. Filtered water samples were analysed for NH_4-N, NO_2-N, NO_3-N, total Kjeldahl-N, phosphate (PO_4^{3-}-P), total phosphorus (total-P), sulphate (SO_4^{2-}), iron (Fe) and calcium (Ca^{2+}) in the Laboratory of Plant Biochemistry of the Estonian Agricultural University following standard methods for the examination of water and wastewater quality (APHA 1989). Groundwater discharge was estimated on the basis of both Darcy's law and through gauging with weirs installed in groundwater seeping sites. Average annual input discharge was estimated to be 8.3 ± 3.5 m^3 ha^{-1} d^{-1}. Meteorological analyses are based on precipitation, air temperature, wind velocity and humidity data, measured six times a day, as well as daily, monthly and annual averages from the Ülenurme Meteorology Station of the Estonian Meteorology and Hydrology Institute (EMHI). The station is located near the weir of the Porijõgi transect. Mean annual precipitation for the study period varied from 555 to 711 mm.

Soil sampling and analyses in the Estonian study area

In Porijõgi, three soil samples of 50 cm^3 were taken at two depths (0–10 cm and 10–20 cm) from all plant communities through the riparian buffer zone. Sampling was carried out twice a year: in spring (May) and autumn (October). Soil pH value, organic matter (loss of ignition), Kjeldahl-N, and lactate-soluble P concentrations were analyzed in all soil samples using the standard methods (APHA 1989).

Calculations and statistical analyses

In order to estimate the final N_2-N flux values, we used the N_2:N_2O ratio calculated using the He-O method. The GWP of the studied systems was calculated by converting the fluxes of N_2O and CH_4 into CO_2 equivalents (IPCC 2001).

The normality of variable distributions was checked using the Kolmogorov-Smirnov, Lilliefors, and Shapiro-Wilk's tests. In most cases for gas analyses, the distribution differed from the normal distribution, and hence non-parametric tests were performed. Medians, 25% and 75% percentiles and non-outlier range values of variables are presented. We used the Kruskal-Wallis ANOVA and multiple comparison of mean ranks to check the significance of differences between the gas fluxes at different sites. For CH_4-C, the Duncan test was used. The Mann-Whitney *U*-test was used to check the difference between the gas fluxes in the study areas in Estonia and Germany. The statistical analysis was carried out using Statistica ver. 7.1 (StatSoft Inc.). The level of significance of $\alpha = 0.05$ was accepted in all cases.

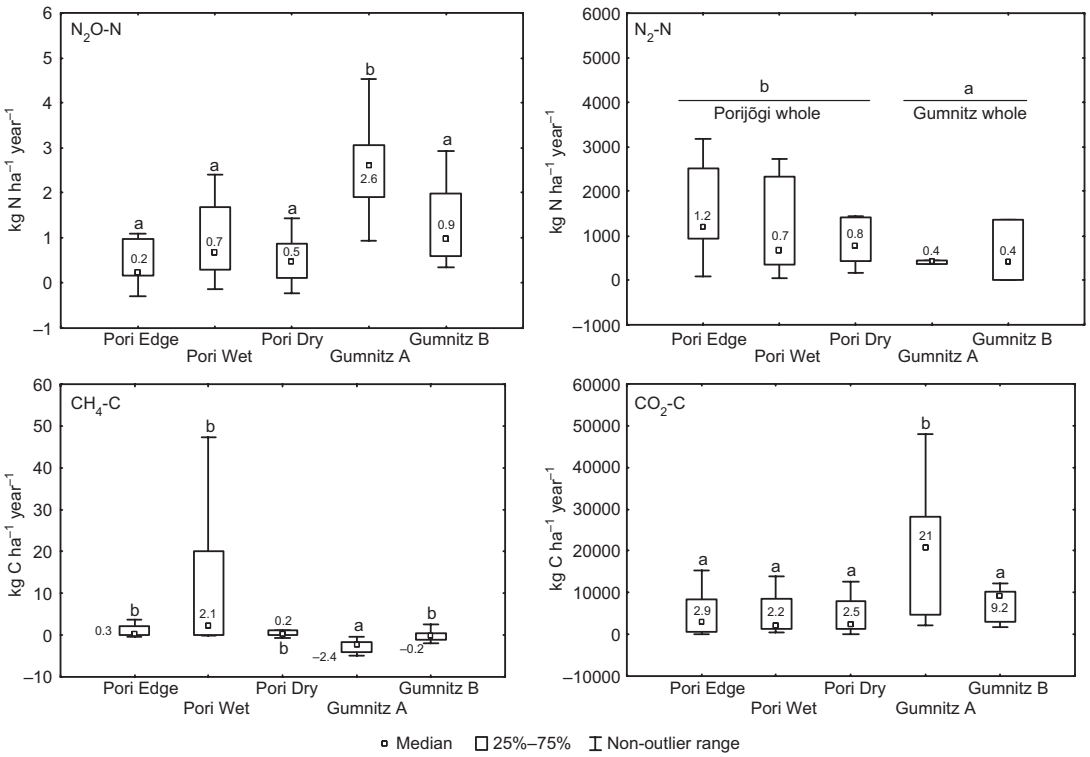

Fig. 1. Median, 25% and 75% percentiles and non-outlier ranges of N_2O, N_2, CH_4, and CO_2 fluxes from three sites (Edge, Wet, Dry) of the Porijõgi grey alder stand and two sites (A, B) of the Gumnitz black alder stand. Nitrous oxide and CH_4 fluxes are given in kg ha^{-1} year^{-1}, and N_2 and CO_2 are given in t ha^{-1} year^{-1}. Numbers indicate median values, and letters show significantly ($p < 0.05$) differing values according to the multiple comparison of test sites: for CO_2, N_2O and N_2 using the Kruskal-Wallis test, and for CH_4 using the Duncan test.

Results

Gaseous emissions

We found remarkable differences in the median values of gaseous emissions between different study sites (Fig. 1). Riparian grey alder sites emitted significantly less N_2O-N than black alder sites: the median values for N_2O flux varied from 0.2 to 0.7 and from 0.9 to 2.6 kg N ha^{-1} year^{-1} respectively, and for N_2 flux from 700 to 1200 and from 360 to 400 kg N ha^{-1} year^{-1} correspondingly (Fig. 1). No significant difference was found between different sites in the grey alder forest, while the N_2O-N flux in black alder stand with altered water regime (Gumnitz A: 2.6 kg N ha^{-1} year^{-1}) was significantly higher than in the black alder stand with unchanged water regime (Gumnitz B: 0.9 kg N ha^{-1} year^{-1}; Fig. 1). No significant differences between N_2-N:N_2O-N ratios in Estonian grey alder stands were found.

The CH_4 emission showed elevated values in the grey alder sites, and was highest in wetter conditions (Porijõgi Wet: 2.1 kg C ha^{-1} year^{-1}). At the same time, the black alder forests acted as a methane sink (–0.2 and –2.4 kg C ha^{-1} year^{-1} in Gumnitz B and A, respectively; Fig. 1).

The emission of CO_2-C was highest in the black alder forest with lowered water table (Gumnitz A: 21 t C ha^{-1} year^{-1}), whereas no significant differences were found between the study sites in the grey alder forest (2.2–2.9 t C ha^{-1} year^{-1}; Fig. 1).

Global warming potential of studied systems

The studied riparian buffer zones did show relatively high GWP values: from 1356–1547 kg CO_2-C equivalents (eq) ha^{-1} year^{-1} in Porijõgi to 4870–11 130 CO_2-C eq ha^{-1} year^{-1} in Gumnitz

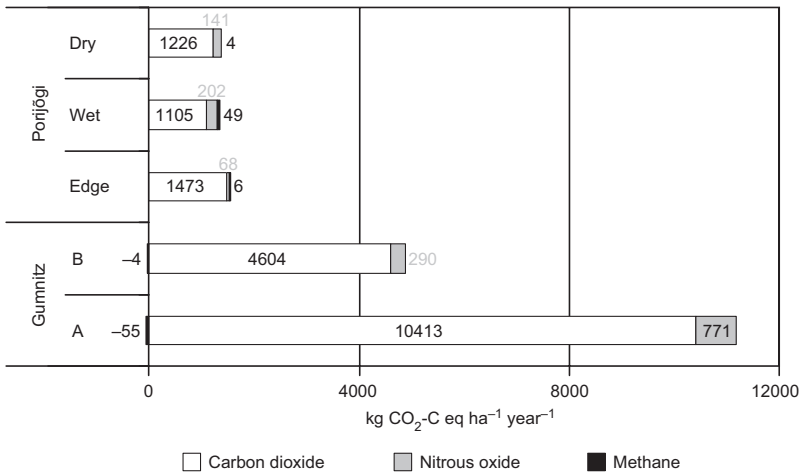

Fig. 2. The share of major greenhouse gases from the Porijõgi and Gumnitz riparian study sites from October 2001 to November 2003, presented as median CO_2 equivalent values (kg CO_2-C ha^{-1} $year^{-1}$). The conversion of the flux rates into CO_2 equivalents is given with 296 for N_2O and 23 for CH_4 in a time horizon of 100 years (IPCC 2001). Carbon dioxide values are reduced by 50% assuming that this proportion can be assimilated in photosynthesis (*see* Butnor *et al.* 2003).

(Fig. 2). Carbon dioxide constituted the largest part of the total GWP of the riparian alder forests, showing average values of 1473, 1105 and 1226 kg CO_2-C eq ha^{-1} $year^{-1}$ in Porijõgi Edge, Wet and Dry sites, respectively, and 10 413 and 4604 kg CO_2-C eq ha^{-1} $year^{-1}$ in Gumnitz A and B sites, correspondingly (Fig. 2). The share of N_2O in GWP was significantly higher in the black alder stands in Gumnitz (290–791 kg CO_2-C eq ha^{-1} $year^{-1}$) than in the grey alder stand in Porijõgi (68–202 kg CO_2-C eq ha^{-1} $year^{-1}$; Fig. 2). The share of methane fluxes in GWP was very low, while it was negative in the black alder stands at both Gumnitz sites (–4 to –55 kg CO_2-C eq ha^{-1} $year^{-1}$).

Discussion

Several investigations into N_2O and CH_4 emissions from riparian zones show significant variability in emission rates, as well as in the percentage share of N_2O-N in the N load (Table 2). The N_2O and CH_4 fluxes have ranged from –0.22 to 20 kg N_2O-N ha^{-1} $year^{-1}$ and from –4.4 to 36 kg CH_4-C ha^{-1} $year^{-1}$, while the share of N_2O-N emission in the total N input has varied from 0.02% to 4.2%. Likewise, our earlier studies showed a remarkable variability of greenhouse gas emissions from the Porijõgi alder forest (Mander *et al.* 2005, Teiter and Mander 2005)

Dinitrogen emission was the most important component of N retention within the Porijõgi riparian grey alder forest. The estimated N_2-N emission for 1994–1995 was 51.2 kg N ha^{-1} $year^{-1}$ (Lõhmus *et al.* 2002), while the latest measurements in 2001–2003 gave median values as high as 700–1200 kg N ha^{-1} $year^{-1}$. The intensive N_2 emission from the Porijõgi test area can be related to the high microbial activity in alder forests (Hart *et al.* 1997, Dilly *et al.* 2000, Lõhmus *et al.* 2002), which could be assumed to lead to higher denitrification activity. One of the N_2 sources could be denitrification (degassing) in the groundwater, although this has been measured in riparian wetlands (Blicher-Mathiesen *et al.* 1998, Mookherji *et al.* 2003). Mogge *et al.* (1998) found that denitrification in a black alder forest was approximately 15 times greater than in beech forest. The comparison of nitrogen-fixing red alder and Douglas fir forests has shown that denitrification enzyme activity was greater in the alder forest. Also, in alder forest denitrification was limited only by organic matter and not by NO_3^-, whereas in Douglas-fir soils it was frequently limited by both NO_3^- and energy (Griffiths *et al.* 1998). On the other hand, the CH_4 oxidation capacity in alder forests has

been found to be significantly lower than in other forests (Reay *et al*. 2001, 2005). This explains the higher CH_4 emission values in alder stands (*see* the Wet site in Porijõgi; Fig. 1).

To determine the possible impact of stand age and site conditions on the forms of N emission, we measured gaseous emissions from additional grey alder stands in southern Estonia in July and October 2003. In a Viiratsi riparian grey alder stand (Kuusemets *et al*. 2001, Lõhmus *et al*. 2002, Mander *et al*. 1997) two sites in the 50-year-old part and one in the < 10-year-old buffer strip were involved in the study. In Holvandi, emissions were measured in a 9-year-old grey alder plantation on an abandoned field (Uri *et al*. 2003a) where the soil N pool was 3–4 times lower than in riparian grey alder stands. In all of the grey alder stands studied (Porijõgi, Holvandi, and Viiratsi) the N_2-N:N_2O-N ratio was very high.

In riparian grey alder stands N_2 emissions were significantly lower in 50-year-old sites than in younger ones, which indicates that N_2 emission in alder stands could be higher in earlier successional phases. This is most likely related to changes in microbial activity during the succession of a pioneer grey alder stand into a more stable mixed forest community.

Based on the total inputs and outputs as well as accumulation and transformation rates of nitrogen estimated in our earlier publications (Lõhmus *et al*. 2002, Mander *et al*. 2005) the N budget of the grey alder stand in Porijõgi was established (Fig. 3). Total inputs (kg N ha^{-1} $year^{-1}$), which consist of symbiotic N_2 fixation (184.6), subsurface and overland flow (25.6), deposition of mineral nitrogen (6.4), and non-symbiotic N_2 fixation (0.5), were 217.1 kg N ha^{-1} $year^{-1}$. This relatively high value is due to high symbiotic fixation, whereas the non-symbiotic N_2 fixation was estimated to be negligible.

Nitrogen accumulation in plants after litter fall was 139.4 kg N ha^{-1} $year^{-1}$ (Fig. 3). The annual N accumulation in soil was remarkably high (98.3 kg N ha^{-1} $year^{-1)}$, about half of the fixed N_2-N. The total N demand in the Porijõgi grey alder stand in 1994 was 285.3 kg N ha^{-1} $year^{-1}$; 81.9 kg N ha^{-1} $year^{-1}$ was transformed and assimilated by plants, whereas the litter amounted to 132 kg N ha^{-1} $year^{-1}$ (*see* Lõhmus *et al*. 2002).

Table 2. Emission of nitrous oxide and methane in riparian buffer zones.

Reference	Country	Ecosystem type	N_2O-N emission (kg N ha^{-1} $year^{-1}$)	CH_4-C emission[a] (kg C ha^{-1} $year^{-1}$)	Initial load[a] (kg N ha^{-2} $year^{-1}$)	N_2O % of N input	Comment
Weller *et al*. 1994	USA	Riparian hardwood forest	0.16–0.88[a]	–	24.1–102[a]	0.65–0.87[a]	range of mean values
Jones *et al*. 1995	USA	Riparian (hyporheic) zone in an arid area	–	0.32–14.9[a]	–	–	range
Jacinthe *et al*. 1998	USA	Riparian forested wetland	0.66–11.0[a]	–	65.7–296[a]	0.02–3.7[a]	range
Groffman *et al*. 2000	USA	Riparian forested wetlands	–	–	–	0.09–0.45[a]	range
Hefting *et al*. 2003	The Netherlands	Riparian black alder forest	20.0[a]	–	475[a]	4.2[a]	average value
Teiter & Mander 2005	Estonia	Riparian gray alder forest	–0.22–3.6	–0.44–36	11.0–292	1.2–2	range of mean values
This paper	Germany	Riparian black alder forest	0.44–7.8	–4.4–3.1	–	–	range of mean values

[a] original data given in μg m^{-2} h^{-1} or in mg m^{-2} d^{-1}.

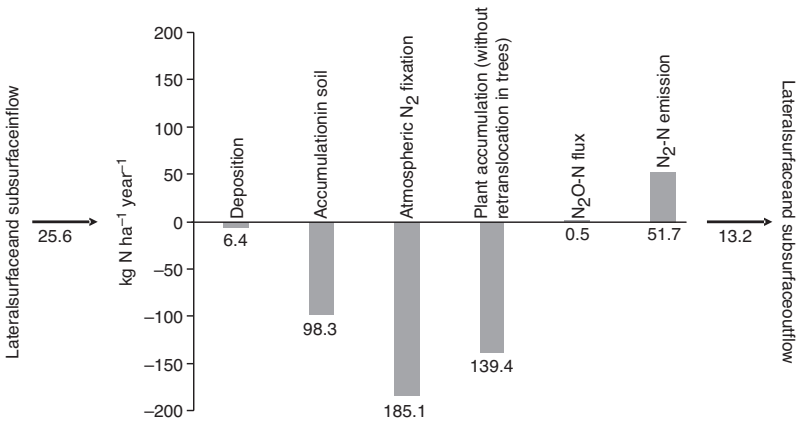

Fig. 3. Nitrogen fluxes (kg ha^{-1} $year^{-1}$) in the Porijõgi grey alder forest in 1994–1995. Compiled after Lõhmus *et al.* 2002.

Nitrogen output into groundwater and streams was 13.2 kg N ha^{-1} $year^{-1}$ (Fig. 3). The estimated N_2-N emission for 1994–1995 was 51.2, whereas emission of N_2O-N, which contributes to global warming and damages the ozone layer, was 0.5 kg N ha^{-1} $year^{-1}$ (Fig. 3). Thus the nitrous oxide flux was 3 orders lower than the dinitrogen emission.

Considering all inputs and outputs, the N removal efficiency in grey alder stands decelerates with increasing age (*see* also Mander *et al*. 2005). Thus grey alder buffer communities should be managed by regeneration cutting and tending so as to keep their N removal rate high**.**

Due to intensive N and C retention, the P retention in alder forests is also remarkable (Giardina *et al*. 1995, Zou *et al*. 1995, Uri *et al*. 2003b, Mander *et al*. 2005). Thus alder forests with intensive internal nutrient cycling work as effective soil producers without significant leaching of nutrients. In riparian zones denitrification is the key factor in balancing N fluxes.

The relatively high CO_2 emission from the Gumnitz study area is related to the significantly higher total C concentration of soils in Gumnitz as compared with that in the Porijõgi study area (20%–40% and 4.0%–5.3%, respectively). In our study, the CO_2 emission is not connected with fluxes related to plant photosynthesis. Therefore only data for cold periods can be considered as losses to the atmosphere. In the calculation of net ecosystem CO_2 exchange, a more advanced measurement technique is required.

However, some studies on C sequestration in wetlands and forest ecosystems (Butnor *et al*. 2003) allow us to estimate that about 50% of the CO_2 released during soil respiration, will in the vegetation period be assimilated by trees through the photosynthesis. Therefore this 50% reduction has been taken into account in our results on CO_2 emissions from forest ecosystems (Fig. 3).

In comparing the greenhouse potential of CH_4 and N_2O over a long time scale (100–500 years), one can speculate that due to the short adjustment time for CH_4 in the atmosphere (8.4 years; IPCC 2001), the radiative forcing of CH_4 will fall relative to CO_2 (Whiting and Chanton 2001). Nitrous oxide, with its atmospheric lifespan of about 120 years and GWP value of 296, however, has a more significant impact. Our data show a minor CH_4 emission from riparian alder forests. Likewise, the N_2O emission was relatively low as compared with emissions from constructed wetlands for wastewater treatment (Teiter and Mander 2005). However, the high radiative forcing value of N_2O makes its share in total GWP remarkable, being highest in the riparian black alder forest with altered water regime (771 kg CO_2-C eq ha^{-1} $year^{-1}$ in Gumnitz A; Fig. 3). The lowering of the water table in wetlands is a well-known reason for N_2O emission (Martikainen *et al*. 1993). The planned increase in fertilization intensity and reconstruction of abandoned drainage systems in several Eastern European countries after the political and socio-economic changes of the 1990s (*see* Mander *et al*. 2000, Stålnacke *et al*. 2003) may change the N balance of riparian ecosystems. However, its dynamics and especially the change in gaseous N fluxes are relatively unpredictable. Therefore

further investigations should concentrate on the factors that regulate N_2O and N_2 emission rates from riparian buffer zones.

Conclusions

Gaseous emissions from the studied riparian alder stands showed significant spatial variation. The median values of N_2O-N, N_2-N and CH_4-C ranged from 0.2 to 2.6, from 360 to 1200 and from –2.4 to 2.1 kg ha^{-1} $year^{-1}$, respectively. The CO_2-C fluxes varied from 2.2 to 21 t ha^{-1} $year^{-1}$. In the grey riparian alder forest sites the CH_4 and N_2 fluxes were higher and the CO_2 and N_2O fluxes were lower than in the black alder sites.

Dinitrogen emission was found to be the most important component in N retention from the studied riparian grey alder forests (up to 1200 kg N_2-N ha^{-1} $year^{-1}$). On the other hand, we found a significantly higher N_2-N emission and lower N_2O-N flux from the grey alder stand on mineral soils than from the black alder stands on organic soils. Nitrous oxide emission was significantly higher in a study site with a lowered groundwater table, while the methane emission showed higher values in wetter conditions at Porijõgi Wet Site.

Carbon dioxide constituted the largest part of the total GWP of riparian alder forests, being significantly higher in black alder sites (from 4604 to 10413 kg CO_2-C eq ha^{-1} $year^{-1}$) as compared with that in the grey alder sites (from 1105 to 1473 kg CO_2-C eq ha^{-1} $year^{-1}$). The share of N_2O in the GWP was also significantly higher in the black alder stands: 290–771 and 68–202 kg CO_2-C eq ha^{-1} $year^{-1}$ for black alder and grey alder stands, respectively.

Riparian grey alder forests as pioneer communities are optimal buffer zones, and their N removal capacity is high despite the N accumulation in soil due to symbiotic N_2 fixation. Instead of leaching, in these ecosystems denitrification works down the soil N storage accumulated during succession.

Acknowledgements: This study was supported by EU 5 FP RTD project EVK1-2000-00728 "**PR**ocess Based **I**ntegrated **M**anagement of Constructed and **R**iverine Wetlands for **O**ptimal Control of Wastewater at Catchment **S**cal**E**" (PRIMROSE), the Estonian Science Foundation projects No. 2471, 3885 and 5247, and the Target Funding Project No. 0182534s03 of the Ministry of Education and Science, Estonia.

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